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From: S. Shyam Sunder <sunder@nist.gov>  
To: wtc@nist.gov  
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Subject: FW: WTC Twin Towers Collapse  
Date: 21 Jul 2005 12:34:11 -0400  
X-MailScanner:  
X-MailScanner-From: sunder@nist.gov

-----Original Message-----

From: Paramasivam Jayachandran  
Date: 7/21/05 7:53 am  
To: sunder@nist.gov, simiu@nist.gov  
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Subj: WTC Twin Towers Collapse

Please see enclosed a review of NIST Study on Twin Towers requested by Eric Douglas, IPRC, Independent Peer Review Council.

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# **Collapse of the Twin Towers of World Trade Center**

**National Institute of Standards and Technology, BFRL Study**

**Gaithersburg, MD, 20303**

*Review by*

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## **Introduction**

The collapse of the twin towers of the world trade center, New York, NY, on September 11, 2001, was a tragic event in the history of US practice of structural engineering and design. It also resulted in loss of life for over 3068 people, and severe damage to infrastructure and financial losses in New York. NIST study on the probable causes of collapse of the twin towers was sanctioned by Congress, and was conducted at BFRL, Building and Fire Research Laboratory. This is a review of this study, undertaken at the request of IPRC, Independent Peer Review Council, headed by Eric Douglas, Architects and Engineers. The families of these victims have requested this study.

The twin towers were designed as framed-tube tall buildings, where all lateral loadings were carried by framed-tube at the periphery of each tower. The interior core, consisting of braced frames, carried mainly gravity loads. Framed-tube systems were developed by Dr. Fazlur R. Khan, of Skidmore, Owings and Merrill, Architects and Engineers, Chicago, IL. Well known buildings designed by him and his associates are, Sears Tower and John Hancock Center, Chicago, 110 and 100 story buildings. Sears is a bundled tube, while John Hancock is a diagonal-trussed tube system. They are very stiff, by virtue of their internal cells and exterior diagonal braces. The twin towers did not have these systems, except a single framed-tube at the periphery. The frequencies of these buildings are as follows-0.1282 Hertz, 0.125 Hertz and 0.0911 Hertz. Clearly, the twin towers were more flexible. The twin towers also had a framed-tube made up of box columns with flat plate spandrels, all 14 inches deep, to make uniform sizes, easy for fabrication. The thickness of these elements gradually increased at bottom to resist largest wind moments and shears at bottom. The steel yield strength was varied from A36 at top to 100 ksi steel at bottom. Sears uses only A36 and A572-50 ksi steel. John Hancock uses only A36 steel. The twin towers design was inspired by aircraft design, with stringer-shear panel theory, common in aeronautics. The Sears and John Hancock use traditional wide flange shapes for columns and spandrel girders, as in other tall buildings.

The NIST study is quite comprehensive in its objectives. Elastic, inelastic and nonlinear analyses were made and experiments conducted using substructures, for structural and fire resistance and collapse, due to simulated impact loadings by aircrafts. Probable causes of collapse are given. Design recommendations are made for future design of tall framed-tube buildings. This review examines its methodology and results of the failure analysis.

## The Probable Causes of Collapse of Twin Towers

The NIST study outlines some probable causes of collapse of the two towers. The extensive finite element analysis and experimental model studies of typical elements and substructures have been used to suggest possible modes of failure. This is also supported by video, photographs and media reports on the sequence of collapse of towers 1 and 2.

The events listed are essentially due to aircraft impact damage, the role of the hat truss, interior core and framed-tube to redistribute the loads, once key columns and spandrels were damaged in the walls, where the aircrafts impacted. Redistribution of loads around the severed columns is examined. The role of the hat truss is also studied for its role in redistribution. The loss of fire proofing on key structural elements and subsequent fires at several floors, due to contents burning, are also studied.

The thermal plastic and creep strains in the core, floor system and the framed-tube are examined under impact and thermal loads. The weakening of the structural system due to these extreme strains is assessed, and failure mechanisms are suggested for the initiation of collapse. Local buckling of the framed-tube and the overall buckling of the entire building are deduced from this.

The probable causes of collapse are suggested. The change in potential energy due to the downward movement of several floors, above the already buckled columns in and around the framed-tube walls, was greater than the strain energy, which could be absorbed by floors at lower levels, is suggested to be a probable cause of collapse. The effects of collapsed floors, which consisted of open web trusses, with bent up bars as shear connectors, is not very clearly established. Membrane strength of diaphragms in tall framed-tube, is assured by floor systems, made up of composite steel-concrete construction, with wide flange beams. John Hancock Center, Chicago, has these systems for its floors. Sears has a truss floor system, but it is made up of structural steel angles, for its web and flanges, and stud shear connectors. Twin towers had truss-joists only. This is more flexible than the former.

The floor trusses collapsed first, resulting in the loss of diaphragm stiffness for the framed-tube. Of course, framed-tube walls, where the aircrafts impacted, caused their columns to buckle first, at these locations. Framed-tube could go into a breathing type mode of failure, if its internal diaphragms collapsed first. Dynamic analysis would have predicted this mode. Floor trusses also lost their protective fire proofing, during the explosion due to aircraft fuel, and consequent fire. This has implications for future tall framed-tube building design. NIST report does not discuss this much, except the collapse of floor trusses under fire. Progressive collapse of the tube was probably initiated by the collapse of successive floors.

The effects of several floors falling on to floors below, as impact loads, and an assessment of a dynamic load factor due to these impact loads, are not determined. The dynamic load factors suggested by approximate methods (Bazant, 2002), are not examined. Bazant suggested that it would be of the order of 15 to 20. Most buildings are not designed for such dynamic load factors. Gust effect factors often used in tall building design for wind are of the order of 3 to 4 (Davenport, 1967). Wind tunnel studies reported by the project structural engineers, suggest these values.

Dynamic analysis of the framed-tube building, with diaphragms included for floors, may have been done, by NIST, but not included in the report. This would have explained the dynamic collapse of the twin towers. The overall collapse of the towers is essentially deduced from the elastic, inelastic and nonlinear analyses. Substructures are used for nonlinear and fire response studies. However, a dynamic analysis of the core and the framed-tube are not reported.

The experimental model studies are quite extensive to establish the failure of floor system and its components. However, this is not fully integrated in to an overall collapse of the entire building, made of interior braced-core and exterior framed-tube, and an assessment of a collapse load, is not reported.

## Summary and Conclusions

The NIST study is quite comprehensive in its objectives. It has detailed elastic, inelastic and nonlinear analyses to assess stresses and displacements to suggest possible causes of collapse. However, a dynamic analysis based assessment of collapse loads and mechanisms seem to be not reported. NIST may have carried out such analyses. It may be included in its final reports. Design recommendations should include results of such studies. Virtual work principles could be used to assess effects of overloads, fire and dynamic impact loadings. This would make NIST study more complete and helpful in future design of tall framed-tube buildings. NIST recommendations for fire resistant design and HVAC systems are quite comprehensive. The fire evacuation methods suggested, are also quite detailed, and will be useful for architects, construction engineers and management professionals. Clients and public will be benefited from such recommendations. NIST should also be funded for future research on the design of framed-tube tall buildings, to develop a design methodology, for wind, earthquake, fire and blast loadings. Research proposals could be written at NIST, seeking such funds, in collaboration with universities and consulting firms. NSF does not fund this type of research at present, due to its emphasis on infrastructure and its rehabilitation.

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